*RELATIONS BETWEEN THE SPECTRA AND OTHER CHARACTERISTICS OF THE STARS.**

III.

TO proceed farther we must have recourse to the study of eclipsing variable stars. Methods for computing their orbits have been developed at Princeton during the last few years,[20] the main motive for the investigation being the astrophysical importance of the results. Dr. Shapley, using the methods devised by the speaker, has obtained elements for eighty-seven such systems,[21] for each one of which the density of the components may be calculated. The values here employed are those which result from the assumption that the stars present discs darkened toward the edge, like the sun, but to a still higher degree, and the principal uncertainty of the results (which in any case cannot be very serious) arises from our present ignorance of the actual degree of this darkening. For our present purpose, they may be best utilised by computing the absolute magnitudes which the brighter component of each system would have if its mass and surface brightness were equal to those of the sun, leaving outstanding the differences due to density alone.

The results for the eighty eclipsing variable the elements and spectra of which are known are plotted in Fig. 4, on the same system as in the preceding figures. The black dots represent those stars for which the photometric data are most trustworthy, the open circles those of less precision. We are once more greatly indebted to Prof. Pickering and Miss Cannon for information regarding the spectra of these stars. To the absolute magnitude 4·0 on this diagram corresponds a density 1/3 that of the sun; to 3·0, 1/11; to 2·0, 1/45; to 1·0, 1/180 of the sun's density, and so on.

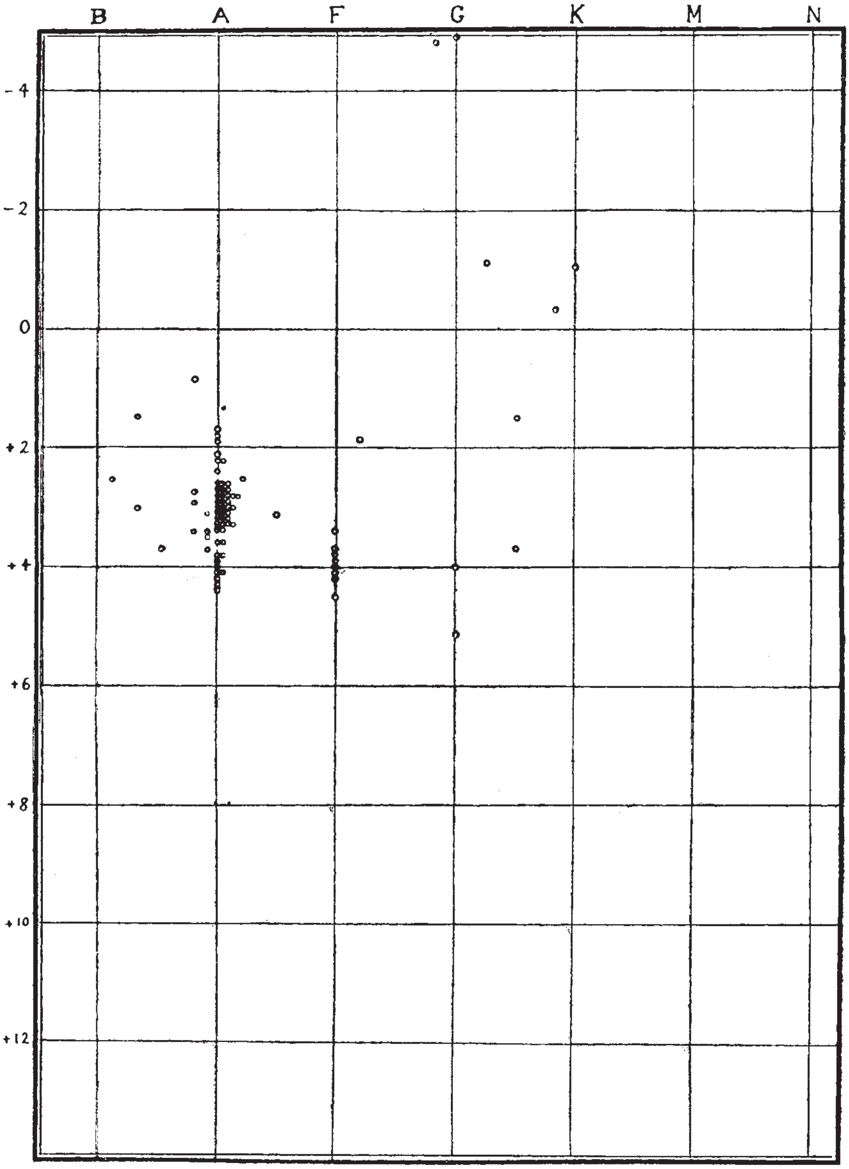

FIG. 4.

This diagram bears at first sight but small resemblance to the previous ones, but a little study brings out several important things. First, though the majority of these eclipsing variables are of Class A, every class from B to K is represented, and there are eight stars of Class G or redder. Secondly, all but one of these eighty stars are less dense than the sun, though but few of them are of less than 1/100 the sun's density. Thirdly, the stars of Classes A and B are fairly similar to one another in density, the great majority having densities between 1/3 and 1/45 of the sun's; those of Class F show a compact group of high density, and an isolated star of low density; but in Classes G and K the range of density is enormously great—from nearly twice that of the sun (W Ursæ Majoris) to one-millionth of the sun's density (W Crucis, at the top of the diagram). Fourthly, among the stars of density less than 1/200 that of the sun (corresponding to about +1·0m. on the diagram), only one of the seventy-one stars of Classes B to F appears, while four of the eight stars of Classes G and K are included. We may now answer decisively, and in the affirmative, the first two questions which were put a few moments ago. Some stars actually have densities quite as low as any that might be required to explain the great brightness of the reddest giant stars; and these stars of low density show a very marked preference for the "later" spectral classes, while practically all the stars of "earlier" type are far denser.

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* An address delivered before a joint meeting of the Astronomical and Astrophysical Society of America and Section A of the American Association for the Advancement of Science, at Atlanta, Georgia, December 30, 1913, with a few additions, by Prof. H. N. Russell. · Continued from p. 258.

[20] *Astrophys Jour.*, vol. xxxv., p. 315, and vol. xxxvi., pp. 54, 239, 385, 1912.

[21] *Astrophys. Jour.*, vol. xxxviii., pp. 159–73, 1913.

We can answer the third question as well, and in a quantitative fashion, if we are willing to assume that the eclipsing binaries, and also the telescopic double stars, of the various spectral classes are typical of the stars of these classes as a whole. Though this may not be rigorously true, there is good reason to believe that it is not seriously in error. We find, from Fig. 4, that the fifty eclipsing stars of Class A, if they all had the sun's mass and surface brightness, but their own densities, would, on the average, be of the absolute magnitude 3·06. Now, referring to Fig. 3, we find that the mean absolute magnitude which the 115 visual double stars of Class AO there recorded would have, if they were equal in mass only to the sun, but had their own surface brightness as well as density, would be 1·07. The only difference between these two groups (if they are both typical of the stars of Class A in general) is that one has been reduced by computation to the sun's surface brightness, while the other has not. It is therefore evident that the stars of Class A must, on the average, for equal surfaces, be two magnitudes brighter than the sun. Apart from the uncertainty whether the two groups compared are exactly typical, the probable error of this determination should be less than one-tenth of a magnitude.

In similar fashion, we find that the mean absolute magnitude of fifty-two visual pairs of spectra Oe5 to B9, reduced to the sun's mass, is −0·4, while that of twelve eclipsing binaries of similar spectrum, reduced to the sun's mass, and surface brightness, is +2·8, which makes the surface brightness of an average star of Class B greater by 3·2m. than that of the sun. Again, for the stars of Class F, we get +2·6 for the mean reduced absolute magnitude of the sixty-nine visual pairs, and +3·7 for that of the nine eclipsing pairs, the difference of 1·1m. being approximately the effect of surface brightness (somewhat more uncertain here, on account of the apparently different proportion of giant stars in the two groups).

It appears, therefore, that in passing down the spectral series from B to G, the surface brightness of the stars decreases by about one magnitude from each class to the next; and we have previously found that, among the dwarf stars, the decrease in surface brightness in passing from G to M must be at least 2½ magnitudes more. All this has been shown without making any use whatever of the physical meaning of the spectra, which have simply been used as symbols in classifying the stars into groups. The results are obviously in accordance with the view that the differences of spectral type arise from differences of temperature. Indeed, they constitute new and important evidence in its favour. How well they agree with other independent lines of evidence is shown by comparing the relative surface brightness just computed with the colour-index for the various classes. Taking A as a standard, we have:—

Spectrum	B	A	F	G	K	M
Surface brightness	−1·2	0·0	+0·9	+2·0	—	+4·5 (at least)
Colour-index ...	−0·3	0·0	+0·3	+0·7	+1·2	+1·6

The computed differences in surface brightness are in all cases about three times the colour-indices, in good agreement with the theoretical ratio.

We may now estimate the density of the redder giant stars. It appears from Fig. 3 that the mean absolute magnitude of the giant stars, if reduced to the sun's mass, is +0·6 for Class G, +0·5 for Class K, and 0·0 for Classes K5 and M. The differences between these values are small, and we may well take the general mean, +0·44, as typical of the whole. This corresponds to about fifty times the sun's luminosity. Such a giant star of Class G, if of the sun's surface brightness, would have to be of about seven times the sun's radius, and of 1/350 of its density. If we assume, on the basis of the foregoing study of the dwarf stars, that the surface intensities of the giant stars of Classes K and M are respectively 1·5 and 3 magnitudes fainter than that of the sun, we find that their densities must be 1/2800 and 1/25,000 of the sun's density. The observed densities of several eclipsing variables of Classes G and K are of just the order of magnitude here found, so that there is direct observational evidence in favour of all our conclusions, except the very low density assigned to the giant stars of Class M (among which no eclipsing variables have yet been found, so that their densities cannot be directly determined). But there is nothing improbable about so low a density, for we know of at least one star—W Crucis—the density of which is still smaller.

Before leaving these diagrams we should notice that, by comparing the data of Fig. 3 with those of Figs. 1 and 2, we may obtain the average masses of the stars of the various types. Consider, for example, the stars of spectra B to B5. From Fig. 3 we see that, if these stars were reduced to the sun's mass without changing either their surface brightness or density, their mean absolute magnitude would be −0·6. But the actual mean absolute magnitude of the stars of this spectral class is −2·0 according to Campbell, or −0·8 according to Boss. Taking the mean of these determinations, we find that these stars are, on the average, 2·1 times as bright as stars of unit mass, but of the same surface brightness and density, would be, from which it follows that their average surface area must be 2·1 times that of the latter stars, and their average mass 3·0 times that of the sun. The uncertainty whether the groups of stars which we are comparing are really exactly similar is here more serious than usual; if Campbell's stars are taken as typical, the mean mass comes out seven times that of the sun. It should be noticed that the "average" mass here obtained corresponds approximately to the average of the logarithms of the individual masses, and hence to their geometrical mean, which will be somewhat smaller than their arithmetical mean, and that we are here dealing with the mass of the brighter component of each system only. For the twelve spectroscopic binaries of spectrum B, which are available for comparison, the mean mass of the brighter components is about 9, and the geometrical mean probably about 7·5, times the sun's mass. As the observational selection in this case undoubtedly favours the larger masses, there is no serious discrepancy between the two results.

Proceeding similarly for the stars of the other spectral classes, we obtain the results collected in Table VII. The observed absolute magnitudes of the stars in clusters have been taken in preference to those of the stars of directly measured parallax, for the reasons already stated, and for the giant stars the mean of the results of Boss and Campbell has been used (except for Class G, for which Boss's value alone really represents them).

Table VII.

Mean Masses of Bright Components of Double Stars.

Spectrum	Observed absolute mag.	Abs. mag. reduced to sun's mass	Resulting average mass
B2	−1·4	−0·6	3·0
A0	+0·5	+1·1	2·3
A5, dwarf	+1·5	+1·6	1·2
F0 ,, ...	+2·4	+2·8	1·7
F3 ,, ...	+3·3	+3·1	0·8
F8 and G0 ...	+4·8	+4·0	0·5
G5, dwarf	+5·1	+4·2	0·3
K0 ,, ...	+6·4	+5·5	0·3
K5 and M, dwarf	+8·9	+7·7	0·2
G and G5, giant	−0·2	+0·6	3·0
K0, giant ...	+0·2	+0·5	1·5
K5 and M, giant	−0·3	0·0	1·5

The general similarity in mass among the stars of such widely different characteristics is very striking. In view of the small numbers of stars in some of the groups, the differences between the individual values should not be greatly stressed, but the gradual decrease of average mass among the dwarf stars is in accordance with the results of direct measurement. The geometrical mean of the computed masses of the bright components of the eight visual binaries of spectra A to F5, the parallaxes of which have been determined with tolerable accuracy, is 1·8 times the sun's mass; for the ten similar stars of spectra F8 to K it is 0·8. The greater mass of the stars of Class B is scarcely shown by these figures, but on this matter the testimony of the spectroscopic binaries deserves much the greater weight. The important conclusion which may be drawn from Table VII. is that, although the range in mean luminosity among the various groups of stars exceeds ten-thousandfold, the range in the mean masses probably does not exceed twenty-, or at most thirty-fold.

We may now summarise the facts which have been brought to light, as follows:—

(1) The differences in brightness between the stars of different spectral classes, and between the giant and dwarf stars of the same class, do not arise (directly at least) from differences in mass. Indeed, the mean masses of the various groups of stars are extraordinarily similar.

(2) The surface brightness of the stars diminishes rapidly with increasing redness, changing by about three times the difference in colour-index, or rather more than one magnitude, from each class to the next.

(3) The mean density of the stars of Classes B and A is a little more than one-tenth that of the sun. The densities of the dwarf stars increase with increasing redness from this value through that of the sun to a limit which cannot at present be exactly defined. This increase in density, together with the diminution in surface brightness, accounts for the rapid fall in luminosity with increasing redness among these stars.

(4) The mean densities of the giant stars diminish rapidly with increasing redness, from one-tenth that of the sun for Class A to less than one twenty-thousandth that of the sun for Class M. This counteracts the change in surface brightness, and explains the approximate equality in luminosity of all these stars.

(5) The actual existence of stars of spectra G and K, the densities of which are of the order here derived, is proved by several examples among the eclipsing variables, all of which are far less dense than any one of the more numerous eclipsing stars of "early" spectral type, with the sole exception of *β* Lyræ.

Evolution.

These facts have evidently a decided bearing on the problem of stellar evolution, and I will ask your indulgence during the few minutes which remain for an outline of the theory of development to which it appears to me that they must inevitably lead.

Of all the propositions, more or less debatable, which may be made regarding stellar evolution, there is probably none that would command more general acceptance than this—that as a star grows older it contracts. Indeed, since contraction converts potential energy of gravitation into heat, which is transferred by radiation to cooler bodies, it appears from thermodynamic principles that the general trend of change must, in the long run, be in this direction. It is conceivable that at some particular epoch in a star's history there might be so rapid an evolution of energy—for example, of a radio-active nature—that it temporarily surpassed the loss by radiation and led to an expansion against gravity; but this would be, at most, a passing stage in its career, and it would still be true in the long run that the order of increasing density is the order of advancing evolution.

If, now, we arrange the stars which we have been studying in such an order, we must begin with the giant stars of Class M, follow the series of giant stars, in the reverse order from that in which the spectra are usually placed, up to A and B, and then, still with increasing density, though at a slower rate, proceed down the series of dwarf stars, in the usual order of the spectral classes, past the sun, to those red stars (again of Class M), which are the faintest at present known. There can be no doubt at all that this is the order of increasing density; if it is also the order of advancing age, we are led at once back to Lockyer's hypothesis that a star is hottest near the middle of its history, and that the redder stars fall into two groups, one of rising and the other of falling temperature.[22] The giant stars then represent successive stages in the heating up of a body, and must be more primitive the redder they are; the dwarf stars represent successive stages in its later cooling, and the reddest of these are the farthest advanced. We have no longer two separate series to deal with, but a single one, beginning and ending with Class M, and with Class B in the middle, all the intervening classes being represented, in inverse order, in each half of the sequence.

The great majority of the stars visible to the naked eye, except perhaps in Class F, are giants; hence for most of these stars the order of evolution is the reverse of that now generally assumed, and the terms "early" and "late" applied to the corresponding spectral types are actually misleading.

This is a revolutionary conclusion; but, so far as I can see, we are simply shut up to it, with no reasonable escape. If stars of the type of Capella, *γ* Andromedæ, and Antares represent later stages of development of bodies such as *δ* Orionis, *α* Virginis and Algol, we must admit that, as they grew older and lost energy, they have expanded, in the teeth of gravitation, to many times their original diameters, and have diminished many hundred-, or even thousand-fold in density. For the same reason we cannot regard the giant stars of Class K as later stages of those of Class G, or those of Class M as later stages of either of the others, unless we are ready to admit that they have expanded against gravity in a similar fashion. We may, of course, take refuge in the belief that the giant stars of the various spectral classes have no genetic relations with one another—that no one class among them represents any stage in the evolution of stars like any of the others—but this is to deny the possibility of forming any general scheme of evolution at all.

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[22] Phil. Trans., vol. clxxxiv., p. 688, 1902; Proc. Roy. Soc., vol. lxv., p. 186, 1899.

We might be driven to some such counsel of despair if the scheme suggested by the observed facts should prove physically impossible; but, as a matter of fact, it is in conspicuous agreement with the conclusions which may be reached directly from elementary and very probable physical considerations.

There can be very little doubt that the stars, in general, are masses of gas, and that the great majority of them, at least, are at any given moment very approximately in stable internal equilibrium under the influence of their own gravitation, and very nearly in a steady state as regards the production and radiation of heat, but are slowly contracting on account of their loss of energy. Much has been written upon the behaviour of such a mass of gas by Lane, Ritter, and several later investigators,[23] and many of their conclusions are well established and well known. So long as the density of the gaseous mass remains so low that the ordinary "gas laws" represent its behaviour with tolerable accuracy, and so long as it remains built upon the same model (*i.e.*, so long as the density and temperature at geometrically homologous points vary proportionally to the central density or temperature), the central temperature (and hence that at any series of homologous points) will vary inversely as the radius. This is often called Lane's law. If, after the contraction, the star is built only approximately on the same model as before, this law will be approximately, but not exactly, true.

The temperature of the layers from which the bulk of the emitted radiation comes will also rise as the star contracts, but more slowly, since the increase in density will make the gas effectively opaque in a layer the thickness of which is an ever-decreasing fraction of the radius. The temperature of the outer, nearly transparent gases, in which the line absorption takes place, will be determined almost entirely by the energy density of the flux of radiation through them from the layers below—that is, by the "black-body" temperature corresponding to this radiation as observed at a distance.

As the gaseous mass slowly loses energy and contracts, its effective temperature will rise, its light will grow whiter, and its surface brightness increase, while corresponding modifications will occur in the line absorption in its spectrum. Meanwhile, its diameter and surface will diminish, and this will at least partially counteract the influence of the increased surface brightness, and may even overbalance it. It cannot therefore be stated, without further knowledge, in which direction the whole amount of light emitted by the body will change.

This process will go on until the gas reaches such a density that the departures of its behaviour from the simple laws which hold true for a perfect gas become important. Such a density will be first reached at the centre of the mass. At the high temperatures with which we are dealing, the principal departure from the simple gas laws will be that the gas becomes more difficultly compressible, so that a smaller rise in temperature than that demanded by the elementary theory will suffice to preserve equilibrium after further contraction. The rise in temperature will therefore slacken, and finally cease, first at the centre, and later in the outer layers. Further contraction will only be possible if accompanied by a fall of temperature, and the heat expended in warming the mass during the earlier stages will now be gradually transmitted to the surface and liberated by radiation, along with that generated by the contraction. During this stage, the behaviour of the mass will resemble, roughly, that of a cooling solid body, though the rate of decrease of temperature will be far slower. The diameter and surface brightness will now both diminish, and the luminosity of the mass will fall off very rapidly as its light grows redder. It will always be much less than the luminosity of the body when it reached the same temperature while growing hotter, on account of the contraction which has taken place in the interval, and this difference of luminosity will be greater the lower the temperature selected for the comparison. Sooner or later, the mass must liquefy, and then solidify (if of composition similar to the stellar atmospheres), and at the end it will be cold and dark; but these changes will not begin, except perhaps for a few minor constituents of very high boiling point, until the surface temperature has fallen far below that of the stars of Class M (about 3000° C.).

The "critical density" at which the rise of temperature will cease can only be roughly estimated. It must certainly be much greater than that of ordinary air, and (at least for substances of moderate molecular weight), considerably less than that of water. Lord Kelvin,[24] a few years ago, expressed his agreement with a statement of Prof. Perry's that "speculation on this basis of perfectly gaseous stuff ought to cease when the density of the gas at the centre of the star approaches one-tenth of the density of ordinary water in the laboratory."

It is clear from the context that this refers rather to the beginning of sensible departures from Lane's law than to the actual attainment of the maximum temperature, which would come later; and it seems probable, from the considerations already mentioned, that the maximum temperature of the surface would be attained at a somewhat higher density than the maximum central temperature.

The resemblance between the characteristics that might thus be theoretically anticipated in a mass of gas of stellar dimensions, during the course of its contraction, and the actual characteristics of the series of giant and dwarf stars of the various spectral classes is so close that it might fairly be described as identical. The compensating influences of variations in density and surface brightness, which keep all the giant stars nearly equal in luminosity, the rapid fall of brightness among the dwarf stars, and the ever-increasing difference between the two classes, with increasing redness, are all just what might be expected. More striking still is the entire agreement between the actual densities of the stars of the various sorts and those estimated for bodies in the different stages of development, on the basis of the general properties of gaseous matter. The densities found observationally for the giant stars of Classes G to M are such that Lane's law must apply to them, and they must grow hotter if they contract; that of the sun (a typical dwarf star) is so high that the reverse must almost certainly be true; and the mean density of the stars of Classes B and A (about one-ninth that of the sun, or one-sixth that of water) is just of the order of magnitude at which a contracting mass of gas might be expected to reach its highest surface temperature.

We may carry our reasoning farther. Another deduction from the elementary theory (as easily proved as Lane's law, but less generally known) is that, in two masses of perfect gas, similarly constituted and of equal radius, the temperatures at homologous points are directly proportional to their masses. As in the previous case, the effective surface temperature of the more massive body will be the greater, though to a less degree than the central temperature. A large mass of gas will therefore arrive at a higher maximum temperature, upon reaching its critical density, than a small one. The highest temperatures will be attained only by the most massive bodies, and all through their career these will reach any given temperature at a lower density, on the ascent, and return to it at a higher density, on the descending scale, than a less massive body. They will therefore be of much greater luminosity, for the same temperature, than bodies of small mass if both are rising toward their maximum temperatures. On the descending side the difference will be less conspicuous. Bodies of very small mass will reach only a low temperature at maximum, which may not be sufficient to enable them to shine at all.

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[23] An excellent summary may be found in Emden's *Gaskugeln*.

[24] NATURE, vol. lxxv., p. 368, 1907.

All this, again, is in excellent agreement with the observed facts. The hottest stars—those of Class B—are, on the average, decidedly more massive than those of any other spectral type. On the present theory, this is no mere chance, but the large masses are the necessary condition—one might almost say the cause—of the attainment of unusually high temperature. Only these stars would pass through the whole series of the spectral classes, from M to B and back again, in the course of their evolution. Less massive bodies would not reach a higher temperature than that corresponding to a spectrum of Class A; those still less massive would not get above Class F, and so on. This steady addition of stars of smaller and smaller mass, as we proceed down the spectral series, would lower the average mass of all the stars of a given spectral class with "advancing" type, in the case of the giants as well as that of the dwarfs. This change is conspicuously shown among the dwarf stars in Table VII., and faintly indicated among the giant stars. The average masses of the giant and dwarf stars appear, however, to be conspicuously different, which at first sight seems inconsistent with the theory that they represent different stages in the evolution of the same masses. But the giant stars which appear in these lists have been picked out in a way that greatly favours those of high luminosity, and hence, as we have seen, those of large mass, while this is not the case among the dwarf stars. The observed differences between them are therefore in agreement with our theory, and form an additional confirmation of it.

It is now easy, too, to understand why there is no evidence of the existence of luminous stars of mass less than one-tenth that of the sun. Smaller bodies presumably do not rise, even at maximum, to a temperature high enough to enable them to shine perceptibly (from the stellar point of view), and hence we do not see them. The fact that Jupiter and Saturn are dark, though of a density comparable with that of many of the dwarf stars, confirms this view.[25]

We may once more follow the lead of our hypothesis into a region which, so far as I know, has been previously practically untrodden by theory. It is well known that the great majority of the stars in any given region of space are fainter than the sun, and that there is a steady and rapid decrease in the number of stars per unit volume, with increasing luminosity. The dwarf stars, especially the fainter and redder ones, really greatly outnumber the giants, the preponderance of which in our catalogues arises entirely from the egregious preference given them by the inevitable method of selection by apparent brightness.

What should we expect to find theoretically? To get an answer, we must make one reasonable assumption, namely, that the number of stars, in any sufficiently large region of space, which is, at the present time, in any given stage of evolution, will be (roughly at least) proportional to the lengths of time which it takes a star to pass through the respective stages.[26] While a star is growing hotter it is large and bright, is radiating energy rapidly, and is also storing up heat in its interior; while, on account of its low density, contraction by a given percentage of its radius liberates a relatively small amount of gravitational energy. It will therefore pass through these stages with relative rapidity. Its passage through its maximum temperature will obviously be somewhat slower. During the cooling stages its surface is relatively small and its rate of radiation slow; it is dense, and a given percentage of contraction liberates a large amount of energy, and the great store of heat earlier accumulated in its interior is coming out again. It must therefore remain in these stages for very much longer intervals of time, especially in the later ones, when the rate of radiation is very small.

This reproduces, in its general outlines, just what is observed—the relative rarity of giant stars, the somewhat greater abundance of those of Class A near the maximum of temperature, and the rapidly increasing numbers of dwarf stars of smaller and smaller brightness. The well-known scarcity of stars of Class B, per unit of volume, is further accounted for if we believe, as has been already explained, that only the most massive stars reach this stage.

In this connection we will very probably be asked, What precedes or follows Class M in the proposed evolutionary series, and why do we not see stars in still earlier or later stages? With regard to the latter, it is obvious that dwarf stars still fainter than the faintest so far observed (which are of Class M) would, even if among our very nearest neighbours, be apparently fainter than the tenth magnitude. We cannot hope to find such stars until a systematic search has been made for very large proper-motions among very faint stars. The extreme redness of such stars would, unfortunately, render such a search by photographic methods less profitable than in most cases.

But a giant star of Class M, a hundred times as bright as the sun, certainly cannot spring into existence out of darkness. In its earlier stages it must have radiated a large amount of energy, though perhaps less than at present. But as the temperature of a radiating body falls below 3000° C., the energy-maximum in its spectrum moves far into the infra-red, leaving but a beggarly fraction of the whole radiation in the visible region. Stars in such stages would therefore emit much less light than they would do later, and stand a poor chance of being seen.[27] We know, as yet, very little about the colour-index and temperature of stars of those varieties of Class M (Mb and Mc) which are evidently furthest along in the spectral series, and it may well be that a star usually reaches the temperature corresponding to these stages by the time that it begins to shine at all brightly. In any case, stars in these very early stages should be of small or moderate luminosity, and rare per unit of volume, and hence very few of them would be included in our catalogues.

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[25] In the foregoing presentation of the theory, to avoid interference with the progress of the main argument, no mention has been made of certain considerations which should be discussed here.

(1) It is probable that at stellar temperatures the gaseous matter is very considerably dissociated and ionised. But this will not affect its gaseous nature. For our present purpose it amounts to little more than a diminution of the mean molecular weight. This will lower the temperature corresponding to a given density and pressure, and so tend to lower the maximum attainable temperature; but as the degree of dissociation is likely to vary gradually with the temperature, it should not affect the orderly sequence of changes which form the basis of the previous arguments.

(2) It is also probable that the available potential energy of a star is not entirely gravitational, but partly, if not mainly, of radio-active or similar atomic origin. If, as in the relatively very small range accessible to experimental investigation, the rate of liberation of this energy is independent of the temperature and pressure, it would simply supply a constant annual addition to the energy derived from gravitational contraction, and the only difference in the course of events would be that a star, on cooling, would approach, not complete extinction, but a steady state, of very long duration, in which as much energy was annually radiated away as was supplied by atomic disintegration. If the rate of disintegration is increased under the extremely violent molecular collisions which must occur in the interior of a star, a great liberation of energy may occur when the interior has got hot enough, thus increasing the maxima temperature and prolonging its duration. But, even on this hypothesis, the number of the violent collisions which liberate the atomic energy would increase gradually as the temperature of the interior rose, and the general character of the evolutionary changes, including the relation of the mass and density of the body to the time of their occurrence, would not be radically altered.

It seems, therefore, probable that the previous reasoning would require no essential modification on account of either of these factors in the problem.

[26] Hertzsprung, *Zeitschrift für Wissenschaftliche Photographie*, vol. iii, p. 442, 1905.

The great luminosity and extreme redness of the stars of Class N suggest that they belong at the beginning of the series of giant stars; but the relations of this very distinct spectral type to the others are not yet quite clear, and it would be premature to give it a definitive place in the sequence. It seems clear, however, that these stars must be in a very primitive condition, rather than in a very late one, as believed by Lockyer. The stars of Class O (Wolf-Rayet stars) are of very great average luminosity, and probably lie beyond those of Class B at the apex of the temperature scale, as Lockyer supposes. But in the absence of data concerning their masses, densities, and the like, we cannot place them definitively, except that Oe5 and Oe come almost certainly just above Bc.

One further application of the theory may be very briefly mentioned. If we have a large number of contracting masses of gas endowed with various moments of momentum, more and more of them will split up into pairs as they grow denser, and the pairs latest formed will have the shortest periods. A large percentage of spectroscopic binaries, especially of short period, is therefore direct evidence of a fairly advanced state of evolution, and the occurrence of this condition among the stars of Classes B and A supports—indeed, almost by itself compels—the view that they are far removed from a primitive condition. Most of the stars which have been investigated for radial velocity are giants, and the absence of spectroscopic binaries of short period among the redder stars is in agreement with the view that they are in earlier stages of evolution.

The distribution of the visual binaries and physical pairs among the various spectral classes depends mainly upon a quite different factor, namely, the resolving power of our telescopes, which allows us to separate the closer pairs of short period only among the nearer stars, so that the systems for which orbits have been determined are nearly all dwarf stars.

I have endeavoured in the past hour to set before you the present state of knowledge concerning the real brightness, masses, densities, temperatures, and surface brightness of the stars, and to sketch the theory of stellar evolution to which the study of these things has led me. This theory is inconsistent with the generally accepted view. Its fundamental principle is identical with that of Lockyer's classification, but it differs radically from the latter in the principles according to which it assigns individual stars, and even whole classes of stars, to the series of ascending or descending temperature. (For example, Lockyer puts such conspicuously giant stars as Canopus, Capella, Arcturus, and β Cygni, and all the stars of Class N, into the descending series, and places β Hydri and δ Pavonis (which are clearly dwarf stars) in the ascending series.)

Two things have gone farthest to convince me that it may be a good approximation to the truth—the way in which it explains and coordinates characteristics of the different spectral types which previously appeared to be without connection or reason, and the way in which a number of apparent exceptions to its indications have disappeared, one by one, as more accurate information concerning spectra, orbits of double stars, and the like, became available, until only one doubtful case remains.

I have purposely made no attempt at this time to touch upon certain other interesting matters, such as the difference of the mean peculiar velocities of stars of the various spectral classes, although, with the aid of simple and very reasonable assumptions, they may be added to the list of things explainable by the new theory. My reason for this has been less for lack of time than because there is at present no definite reason, assignable from general considerations in advance, why we should expect an old star to be moving faster or slower than a younger one, while there is such a reason why we should suppose that a dense star is in a later stage of evolution than one of low density. It seems better to find out what we can about the order of evolution from data of the latter kind, and then apply our results to the study of problems of the former sort, than to attack them without such aid or by means of unproved assumptions. The assumptions that are necessary on the new theory are simple and probable enough, but they do not form an integral part of the theory, and cannot be established directly from general considerations, and so I will not discuss them now.

The new theory will not explain everything about the stars—I should be rather afraid of it if it did; for example, it leaves the phenomena of preferential motion, or "star-streaming," as puzzling as ever. I have only tried to interpret some of the facts most obviously capable of evolutionary explanation, on the fundamental assumption that the properties of matter, and the forces in operation, among the stars, are the same as those with which we are familiar in the laboratory. He would be a bold man indeed who would assert that this assumption is entirely true, but it seems clear that it should be thoroughly tried out before the existence of new forces can legitimately be postulated.

If the ideas to which you have so kindly listened to-day shall prove of any help toward removing the need for belief in unknown forces, and extending the domain of those already known, my labour will be far more than repaid; but it should not be forgotten that the real labourers have been those who, through long and weary nights, accumulated bit by bit, and, through monotonous days, prepared for the use of others the treasures of observational knowledge with which it has been my pleasurable lot to play in the comfort of my study.

I need scarcely add that, if what I have said proves of interest to any of you, your frank and unsparing criticism will be the greatest service which you can render me.

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[27] Russell, *Science*, N.S. Vol. xxxvii, p. 646, 1913.

UNIVERSITY AND EDUCATIONAL INTELLIGENCE.

BIRMINGHAM.—At its last meeting the University council passed the following resolution:—"That the council desires to record its deep sorrow at the death of Prof. Poynting, who so faithfully served the Mason College and the University for thirty-four years. During his distinguished career as professor of physics he was not only an inspiring teacher and investigator, but bore a considerable part in the development of the college and of the University. His keen interest in all that concerned the University, its staff, and its students, his genial and attractive personality, will be long and affectionately remembered; his death leaves a gap which it will be most difficult to fill."